SYNCHRONIZATION OF COMBUSTION VARIATIONS IN A MULTICYLINDER SPARK IGNITION ENGINE

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We report experimental observations of synchronization among combustion variations in different cylinders at fuel-lean conditions in an eight-cylinder spark ignition engine. Our results appear to confirm that synchronization readily occurs and that it becomes stronger as the overall equivalence ratio is reduced from stoichiometric. It also appears that the onset of synchronization is associated with bifurcation instabilities reported previously for combustion in single cylinders. We use both cross-correlation and symbolic time series analysis to quantify the apparent relationships between pairs of cylinders and multicylinder groups. Extension of a simple dynamic model for single-cylinder combustion variations to the multicylinder case appears to agree with the observations and provides a basis for further studies. The occurrence of significant cylinder-to-cylinder synchronization may have significant implications for engine diagnostics and control.

Introduction

Fuel-lean operation of spark ignition engines is of growing importance for reducing emissions and improving fuel efficiency. One of the major practical constraints to lean operation has been the onset of combustion instabilities near the lean limit, resulting in an unacceptable level of misfires and partial burns. Thus, there is considerable interest in understanding the fundamental causes of lean combustion instability and how the negative effects can be minimized.

Recent studies of cycle-to-cycle combustion variations within a single cylinder have shown that the behavior under lean fueling conditions is consistent with the onset of a noisy period-doubling bifurcation sequence [1–5]. Such instabilities are a common feature of nonlinear dynamical systems in which future behavior is highly sensitive to small changes in past conditions. In the case of lean premixed engine combustion, residual fuel and air have a highly nonlinear effect on subsequent ignition and flame propagation in succeeding combustion strokes. As has been previously demonstrated, the resulting cycle-to-cycle dynamics can be simulated using a simple mapping function that predicts the outcome of future combustion events (within a given cylinder) based on engine operating parameters and the outcome of past combustion events (in the same cylinder). The effects of higher-order phenomena such as in-cylinder fluid turbulence and vaporization of fuel droplets are represented as stochastic perturbations of engine parameters such as residual fraction and as-injected equivalence ratio. The purpose of such a hybrid low-order model is to capture the essential statistical features of the combustion instability without being overwhelmed by details. Thus, one sacrifices information about mixing and fluid turbulence for rapid prediction and the evaluation of large numbers (e.g., thousands) of cycles. This type of model is expected to be most useful for understanding general trends (e.g., for engine diagnostics) or for adaptive feedback control. Practical control applications can be seen in Refs. [6,7], which describe how cycle-resolved feedback can be used to counter combustion instabilities.

In this study, we were interested in determining if lean combustion instability is also associated with cylinder-to-cylinder coupling. Specifically, such coupling can lead to a condition known as synchronization, in which combustion events in one or more cylinders develop some type of predictable pattern relative to each other. This investigation differs from earlier studies [1–5,8,9] in that we are investigating how cylinders behave collectively rather than individually. If synchronization is confirmed, our ultimate objective is to develop real-time diagnostics and controls for this collective behavior.

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14. ABSTRACT

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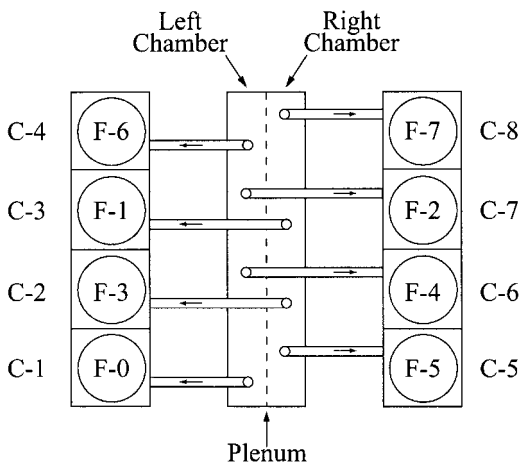| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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FIG. 1. Cylinder and intake manifold configuration. Cylinder location is denoted by C for physical location and F for location in firing order.

Synchronization is a general property of multi-element nonlinear systems, and many examples have been reported [10–14]. Perhaps the most famous example is the case of the synchronizing clocks reported by Christian Huygens in 1673 [13]. Huygens demonstrated that clocks mounted on a common support were synchronized through small mechanical vibrations that were exchanged between them. Similar behavior has been reported in cellular flames [14] and cardiorespiratory systems [12].

Our approach included experimental combustion measurements from a multicylinder engine, analysis of the resulting data, and comparison of our experimental observations with predictions from a low-order model. In the following sections, we describe our experimental setup, data analysis procedures, and the proposed model.

Experimental Apparatus and Procedures

The experiments discussed here were conducted on a 1999 4.6 L, two-valve V-8 Ford Expedition engine. The nominal operating conditions for the experiments were 1200 rpm, 25 N-m brake torque, and 20° BTDC (before top dead center) spark timing. The engine had production port fuel injection with a bore of 90.2 mm, a stroke of 90.0 mm, a compression ratio of 9.0, and a valve overlap of 27 degrees. Engine speed was controlled with an absorbing/motoring General Electric (GE) dynamometer.

In-cylinder pressure measurements were recorded once per crank angle degree at steady-state conditions as equivalence ratio was varied over five equivalence ratios from stoichiometric to very lean fueling conditions. The firing order for the cylinders

was 1-3-7-2-6-5-4-8 (see Fig. 1 for the cylinder layout). Feedback control was engaged to achieve an operating condition; once the condition was achieved, the feedback controllers were shut off, and the engine was run open-loop. The only controller operating during data acquisition was the dynamometer speed controller, which actuated dynamometer torque to maintain constant engine speed. This strategy ensured that the engine combustion dynamics were minimally influenced by controllers.

The memory buffers of the data acquisition system limited contiguous data sets to approximately 354 engine cycles (for all eight cylinders). Repeat sets of contiguous data blocks were collected after a 2 or 3 min pause. For the results described below, three contiguous data blocks were acquired at equivalence ratios of 1.00, 0.83, 0.71, 0.66, and 0.59. All experiments were then repeated a second time to evaluate reproducibility. Net heat release values for each cycle were calculated from the cylinder pressure data utilizing a variant of the Rassweiler and Withrow integration method [15].

Experimental Results

Figure 2a and b illustrates typical heat release patterns in all eight cylinders at stoichiometric and very lean fueling conditions. These plots depict pairs of sequential heat release values for each cylinder and illustrate how each combustion event relates to its successor in time. We note that at near stoichiometric fueling (Fig. 2a), combustion variations are very small, producing a focused cluster of points around the average value. Detailed analysis of these small variations shows that they have a Gaussian distribution and appear to occur randomly in time.

At very lean fueling (Fig. 2b), the picture changes considerably. As shown in Fig. 2, we observe a pattern of variations that is both far from Gaussian distributed and clearly not random. The detailed patterns vary from cylinder to cylinder, but all cylinders exhibit the characteristic hooked shape reported previously for single-cylinder studies [3,5]. Our analyses for each individual cylinder also confirm that the statistical properties of the measurements are consistent with the noisy bifurcation model of Daw et al. [1]. However, for this multicylinder engine there is one complication; each cylinder appears to progress through the bifurcation sequence at a different rate as fueling is leaned. Thus, at each fueling condition, each cylinder is bifurcated to a greater or lesser extent and exhibits a distinctive pattern of combustion variations. We interpret these cylinder-to-cylinder differences as resulting from non-uniformities in the distribution of fuel and air (especially). Such non-uniformities are well known to occur and pose major challenges to engine designers [15].
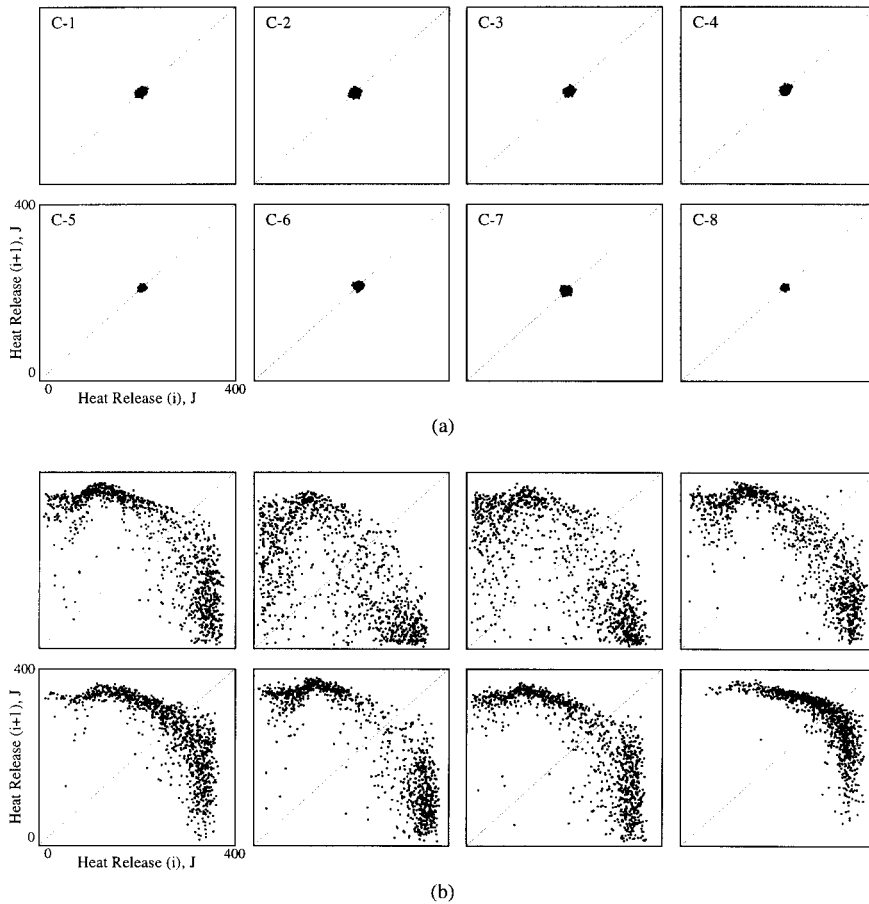
FIG. 2. Heat release return maps for all eight cylinders at (a) stoichiometric and (b) very lean fueling conditions, $\phi = 0.66$. Numbers in (a) refer to cylinder location.

Simultaneous measurements of all eight cylinders allowed us to investigate the possibility that combustion variations in different cylinders might be related. We began by looking for cross-correlations between cylinders, as depicted in Fig. 3. In Fig. 3, we illustrate example behavior over 1000 engine cycles for selected cylinder pairs as fueling was leaned. Note that for one pair (F-0, F-5), a significant positive correlation developed when the as-injected equivalence ratio was adjusted to 0.66. Likewise, a significant anticorrelation appeared simultaneously for the cylinder pair (F-0, F-1), while there appeared to be no significant correlation for the pair (F-0, F-4). Although all possible pairs are not shown in Fig. 3, we observed many cylinder pairs with cross-correlations exceeding 0.2 under lean conditions. We can summarize our observations from such cross-correlations as follows:

• At stoichiometric fueling, we did not observe statistically significant cross-correlations between any

cylinder pairs, implying that combustion variations in each cylinder were effectively independent.
• As fueling was leaned, significant cross-correlations (both positive and negative) developed between combustion variations in some cylinder pairs.
• The distribution of positive and negative cross-correlations among the different cylinder pairs was complex and did not have any obvious relationship to cylinder location or firing order. We observed strong correlations between pairs fed by the same or opposite sides of the intake plenum, pairs on the same or opposing sides of the engine, and pairs close or far apart in firing order. Note that the pairs (F-0, F-5) and (F-3, F-4) have similar physical cylinder locations with respect to each other, but the former pair shows strong correlation under lean conditions while the latter pair shows no significant correlation.
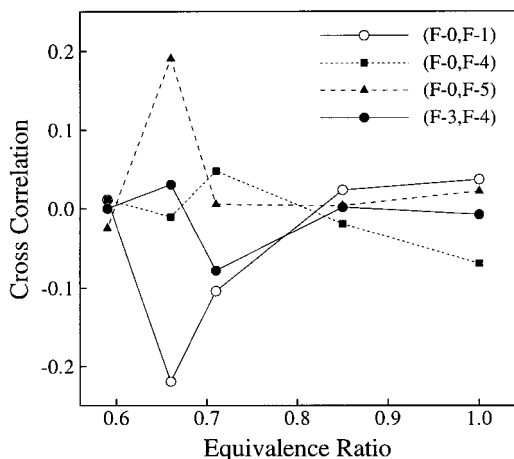• The distribution of lean-fueling cross-correlations

FIG. 3. Cross-correlation between selected cylinder pairs as a function of equivalence ratio. Significant positive and negative cross-correlations occurred at an equivalence ratio of 0.66.

shifted over time. Strong correlations (or anticorrelations) developed between specific pairs, persisted for a significant interval (e.g., tens to hundreds of cycles), and then abruptly reduced in magnitude.

• At extremely lean fueling, combustion became very poor in all of the cylinders, and the cross-correlations between cylinders diminished.

The lack of significant cross-correlations at stoichiometric fueling implies that any potential coupling between cylinders was initially absent or at least had no impact on combustion. Likewise, the occurrence of apparently significant cylinder-to-cylinder correlations at lean fueling implies that some sort of coupling mechanism was activated, allowing some of the cylinders to synchronize with each other. One possible explanation is that uncharacteristically large or small pressure oscillations are induced in the exhaust and intake manifolds when the combustion oscillations in individual cylinders become prominent (i.e., when partial or total misfires occur). Such changes in the pressure oscillations could impact the subsequent intake and exhaust strokes of other cylinders, thereby imposing additional variations in the effective in-cylinder equivalence ratio and stimulating the combustion to change. The apparent variations in bifurcation level from cylinder to cylinder would be expected to complicate the coupling interactions because the stronger oscillating cylinders would tend to drive those with weaker oscillations. While we did not measure the manifold pressure with sufficient accuracy to confirm this scenario in the current experiments, the impact of manifold pressure waves (acoustics) on engine combustion is a widely accepted phenomenon [15].

To further resolve the dynamic relationships between cylinders, it is useful to apply more sophisticated analyses. One method we find to be particularly useful is symbol sequence analysis [2,3]. Briefly, symbolization transforms an original time series of measurements into a sequence of discretized symbols. Such a transformation makes it possible to readily detect and characterize the occurrence of non-random patterns, even when there is considerable experimental noise.

In the case of multicylinder combustion measurements, we are interested in observing non-random patterns over both space and time. One useful symbolization transforms the observed heat release values into a binary data stream (0 or 1) depending on where they fall relative to the median value. For each cylinder, we use the median value for that cylinder so that biases in the nominal fueling levels are discounted. Within the symbolized data, we evaluate interactions between specific cylinder pairs by constructing symbol words (i.e., short symbol sequences) according to the following definition:

$$\mathbf{S2}(j) = [x(j - 1), y(j - 1), x(j), y(j),$$
$$x(j + 1), y(j + 1)] \tag{1}$$

where $S2(j)$ is the symbolic state of the cylinder pair at engine cycle j, and $x(j)$ and $y(j)$ are the symbolic heat release values at cycle j for the first and second cylinder pair members, respectively. For convenience, we refer to each symbol sequence according to its index number defined by:

$$\text{Index}(\mathbf{S2}) = 32x(j - 1) + 16y(j - 1)$$
$$+ 8x(j) + 4y(j)$$
$$+ 2x(j + 1) + y(j + 1) \tag{2}$$

This scheme allows us to uniquely refer to any particular pattern with a single number between 0 and 63.

Figure 4 illustrates how symbol sequence histograms can be used to depict the correlated and uncorrelated cylinder pairs shown previously in Fig. 3. On the abscissa we plot the sequence index number, and on the ordinate we plot the relative frequency at which each possible sequence is observed. At stoichiometric fueling, all sequences are equally probable, and the observed frequencies lie close to the heavy dashed line in Fig. 4. When combustion oscillations develop at lean fueling, peaks become prominent at sequence index values 12, 25, 38, and 51, corresponding respectively to the sequences [0,0,1,1,0,0], [0,1,1,0,0,1], [1,0,0,1,1,0], and [1,1,0,0,1,1]. For uncorrelated behavior (F-0, F-4), the heights of these target peaks are all similar; that is, there is no favored relationship between the cylinder phases. Thus, even when there are considerable oscillations in each cylinder, the lack of coupling means that we are just as likely to observe in-phase
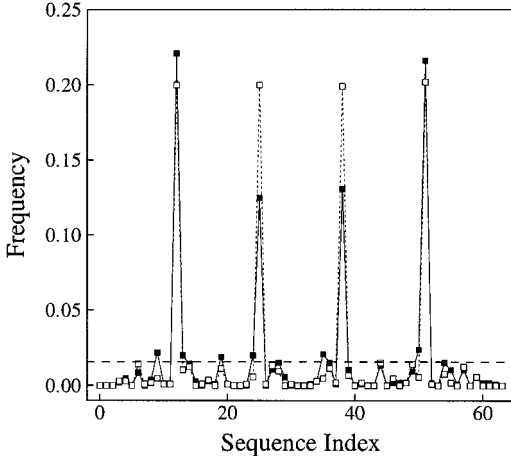
FIG. 4. Example symbol sequence histograms for selected cylinder pairs at very lean fueling conditions, $\phi =$ 0.66. Solid symbols and solid line correspond to cylinder pair (F-0, F-5) which had a significant positive correlation. Open symbols and broken line correspond to pair (F-0, F-4) which had no significant correlation. The heavy dashed line represents the case where all sequences are equally probable, which was approached at stoichiometric fueling.

or out-of-phase behavior. When there is significant correlation (F-0, F-5), the relative heights of peaks 12 and 51 are higher than peaks 25 and 38, indicating that the combustion variations in both cylinders tend to remain in phase more frequently than out of phase. Peaks 25 and 38 are favored for the same reason when the cylinders become anticorrelated. In all cases, the mean height of the four peaks above background levels indicates the degree of joint bifurcation appearing in both cylinders. It is thus possible to use symbol sequence histograms to simultaneously evaluate both the degree of bifurcation and possible coupling.

Figure 5a and b illustrates how symbol synchrograms can be constructed to observe bifurcation and synchronization over time. We plot the observed sequence index against engine cycle number, for example, uncorrelated and anticorrelated cylinder pairs, respectively. For the uncorrelated pair, we observe that all four target peaks occur frequently, but these occurrences are sporadic and distributed evenly over time. Thus, both cylinders are oscillating significantly, but the oscillations are not related to each other in any consistent way. Conversely, for the anticorrelated pair, we observe significantly long uninterrupted periods (episodes) of relatively strong anticorrelated behavior (peaks 25 and 38). Such episodic correlation is suggestive of noisy synchronization.

Synchronization among groups of cylinders larger than two can also be studied using a modified symbol
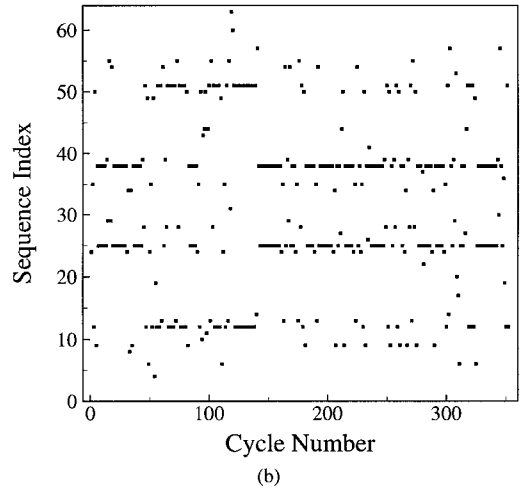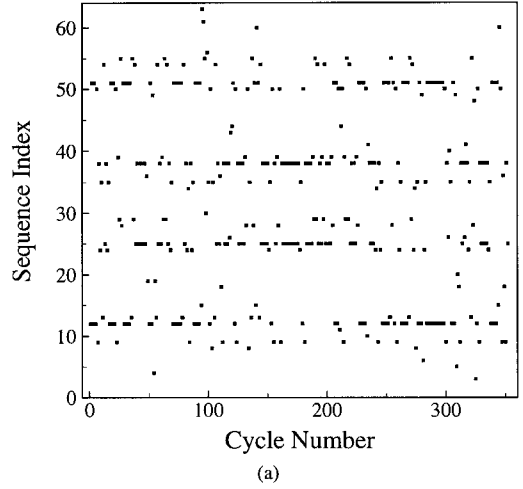

FIG. 5. Symbol synchrograms for (a) uncorrelated and (b) anticorrelated cylinder pairs at very lean fueling conditions, $\phi = 0.66$. Dark bands of repeated symbol sequences reveal combustion oscillations. A persistent bias in these bands indicates apparent synchronization.

sequence definition. Specifically, we define a three-cylinder word as

$$\mathbf{S3}(j) = [x(j - 1), y(j - 1), z(j - 1),$$
$$x(j), y(j), z(j)] \qquad (3)$$

where $x(j)$, $y(j)$, and $z(j)$ are symbolic heat release values for cylinders x, y, and z measured in engine cycle j. The corresponding sequence index is

$$\mathrm{Index}(\mathbf{S3}) = 32x(j - 1) + 16y(j - 1)$$
$$+ 8z(j - 1) + 4x(j)$$
$$+ 2y(j) + z(j) \qquad (4)$$

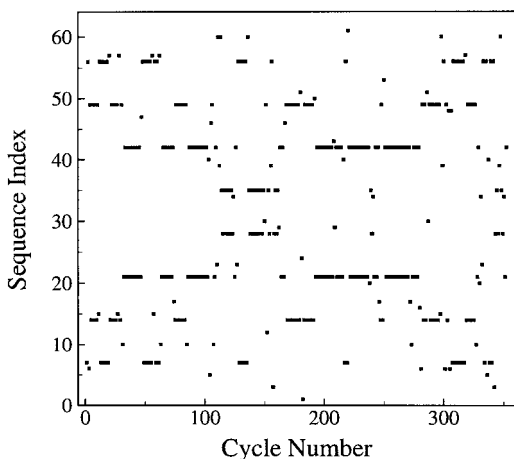Fig. 6 is an example synchrogram based on the above

FIG. 6. Symbol synchrogram for three cylinders (F-0, F-4, F-6) at very lean fueling conditions, $\phi = 0.66$. We observe a persistent bias in the relationship of the three cylinders as a group.
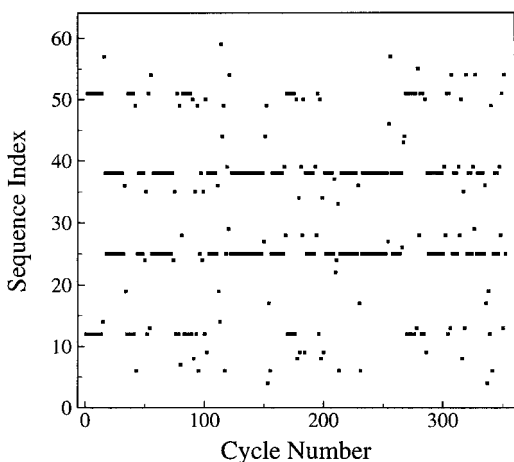

FIG. 7. Symbol synchrogram for anticorrelated model simulation. Persistent bands reveal the anticorrelated coupling deliberately added to the model. The observed patterns are qualitatively similar to the experimental observations for anticorrelated cylinder pairs.

sequence definition applied to two cylinder pairs with a common member. In this case, there appears to be an episodic interaction among all three cylinders. Patterns similar to Fig. 6 were also observed for other three-cylinder groups in our engine.

Proposed Model for Multicylinder Synchronization

Based on the above observations, we conjecture that a model for simulating the observed behavior

can be constructed by adapting the Daw et al. [1] model. Specifically, we suggest that the random noise term used for representing unmodeled engine perturbations should be modified to consist of a random component and a non-random component that reflects intercylinder coupling. From a dynamical systems perspective, this implies that multicylinder engines are more accurately described as noisy coupled map lattices, where each cylinder is a nonlinear mapping function that is coupled in varying degrees to the others. Such a model might be useful for estimating the average coupling between cylinders (e.g., for data fitting). It is also conceivable that adaptive versions of this model (e.g., implemented as a neural network) might be used for on-board diagnostics and control.

To construct such a model, we iterated two replicates of the Daw et al. map, representing two different cylinders in a noisy bifurcated state. We further assumed that the dominant noisy parametric inputs to both cylinders were variations in the as-injected equivalence ratio. These equivalence ratio variations were assumed to be the sum of Gaussian variations (independent for each cylinder) and a small oscillating component that was either correlated or anticorrelated between the cylinders. The oscillating component was intended to represent manifold pressure waves that might effectively couple the cylinders [16]. By varying the relative contribution of the oscillatory component, we studied the predicted effect of coupling. The level of total noise input to each cylinder was kept constant.

Example results of the above model are shown in synchrogram form in Fig. 7. An anticorrelated oscillating noise component was input at 5% (i.e., the percentage of noise variance contributed by the oscillating component). At these conditions, we observed apparent synchronization behavior that was very similar to some of our engine measurements for anticorrelated cylinder pairs (see Fig. 5b). Other similarities observed in the model include:

- For both the model and experiment, the onset of significant cross-correlations coincides with bifurcations.
- Both the model and experiment exhibit transient correlation periods of similar length (e.g., 50–200 cycles).
- The statistical frequencies of the correlation episodes are similar (e.g., interacting cylinders can be synchronized more than 20% of the time once bifurcation occurs).
- The model predicts episodic correlation of multiple cylinder groups (more than two at a time), which we have experimentally observed (see Fig. 6).

Thus, it appears that the model predicts behavior that is at least qualitatively correct.

Summary and Conclusions

Our experimental observations indicate significant cylinder-to-cylinder synchronization where the onset of synchronization corresponds to the development of bifurcations in individual cylinders. Similar behavior has been recently confirmed on a significantly different engine with a different intake manifold [17]. A simple mapping model with a shared noise component to reflect intercylinder coupling exhibits many of the characteristic features observed experimentally. More experimental data are needed to refine the picture of the possible cylinder-to-cylinder interaction patterns. Future studies should address the physical mechanisms responsible for intercylinder coupling. The observation of the reported patterns here in two different multicylinder spark ignition engines could have important implications for engine design and control.

Acknowledgments

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